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WITNESS my hand this
Nineteenth day of August 2003

LEANNE MYNOTT
MANAGER EXAMINATION SUPPORT
AND SALES

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PROVISIONAL SPECIFICATION

Invention Title:

Superconducting quantum interference device

The invention is described in the following statement:

Technical Field

The present invention relates to superconducting devices having elements positioned in three dimensions, and in particular to high temperature superconducting devices having elements positioned in three dimensions. The invention particularly relates to high temperature superconducting axial gradiometers, which employs a gradiometric pick-up loop formed by etching a transformer loop structure on flexible superconducting tape. The pick-up loop is preferably inductively coupled to a superconducting quantum interference device (SQUID) magnetometer. In applications for which the sensitivity to the magnetic field in the direction transverse to the gradiometer axis is problematic, the homogeneous background magnetic field can be reduced by matching the mutual inductance between the secondary loop of the flux transformer and the magnetometer to establish a condition of shielding.

Background Art

Superconducting Quantum Interference Devices (SQUIDs) are often used as highly sensitive magnetic field sensors. Such SQUID sensors are becoming increasingly popular due to the capabilities of high sensitivity sensing in areas such as geophysical mineral prospecting and biological magnetic field detection, such as magnetic field emanations from the human brain or other human organs.

With the advent of high critical temperature superconducting (HTS) materials such as $YBa_2Cu_3O_x$ (YBCO), HTS-SQUIDs can operate at or above 77K (-196°C) and hence can be cooled by relatively inexpensive liquid nitrogen, rather than requiring liquid helium as a coolant for operation at 4K (-269°C). Liquid nitrogen is also more convenient to use than liquid helium, allowing the system as a whole to be made in a compact form.

The use of high-temperature superconducting (HTS) materials for the fabrication of SQUID based magnetometers and gradiometers is now well established (For example, W. Eidelloth, B. Oh, R. P. Robertazzi, W. J. Gallagher, R. H. Koch, Appl. Phys. Lett., **59**, 3473 (1991); S. Knappe, D. Drung, T. Schurig, H. Koch, M. Klinger, J. Hinker, Cryogenics **32**, 881, (1992); M. N. Keene, S. W. Goodyear, N. G. Chew, R. G. Humphreys, J. S. Satchell, J. A. Edwards, K. Lander, Appl. Phys. Lett. **64**, 366 (1994); G. M. Daalmans, Appl. Supercond. **3**, 399, (1995); M. I. Faley, U. Poppe, K. Urban, H.-J. Krause,

H. Soltner, R. Hohmann, D. Lomparski, R. Kutzner, R. Wordenweber, H. Bousack, A. I. Braginski, V. Y. Slobodchikov, A. V. Gapelyuk, V. V. Khanin, Y.V. Maslennikov, IEEE Trans. Appl. Supercond., 7, 3702 (1997)). Despite the significant advantages which accrue from being able to operate at liquid nitrogen temperatures, these materials remain more difficult to use than the alternative low-temperature superconducting materials, and many design practices in low temperature helium cooled superconductors (LTS) cannot be implemented in HTS materials. In particular, the lack of HTS superconducting wires and the difficulty of forming superconducting connections in these materials means that the standard LTS design practice of forming gradiometer coils from superconducting wires, is not applicable in HTS materials.

Designs for HTS gradiometers sensitive to the on-diagonal components, $\partial B_i/\partial x_i$ (axial gradiometers), have been described (for example: R. H. Koch, J. R. Rozen, J. Z. Sun, W. J. Gallagher, Appl. Phys. Lett., **63**, 403,(1993); H. J. M. ter Brake, N. Janssen, J. Flokstra, D. Veldehuis, H. Rogalla, IEEE Trans. Appl. Supercond., **7**, 2545, (1997); J. Borgmann, P. David, G. Ockenfuss, R. Otto, J. Schubert, W. Zander, A.J. Braginski, Rev. Sci. Instrum. 68, 2730,(1997) but these have been implemented only by means of electronic or software subtraction of the outputs of a pair of SQUID magnetometers which are generally positioned at fixed distances from each other on a common normal axis. These designs suffer from the disadvantage that both magnetometers must operate linearly in the full ambient field (often the earth's magnetic field). It is difficult to achieve good common-mode rejection (rejection of homogeneous fields) which is generally limited to order about 10^{-3} in most implementations. Furthermore, the achievable noise performance can be dependent upon the magnitude of the background homogeneous field; being determined by microphonics which arise from vibrations causing randomly varying misalignment of the axes of symmetry of the two SQUIDs.

Some of these problems are ameliorated by the use of intrinsic gradiometer structures. Although several designs for intrinsic magnetic gradiometers utilizing HTS films have been described in the literature[TransGrads] these designs are sensitive only to the off-diagonal components of the first-order gradient tensor, $\partial B_i/\partial x_j,\ i \neq j$ (transverse gradiometers). These designs generally fall into one of two types. The first employs the, now familiar, "figure

eight" topology in which the gradiometic pick-up loop structure consists of a pair of superconducting loops with a common conductor that is interrupted by a direct current (DC) SQUID. The SQUID operates as a two-port device (SQUID amplifier) because the flux in the SQUID is derived from the current directly injected into a pair of input terminals. Depending upon the matching of the inductances and equivalent magnetic areas of the gradiometer input loops the current in the SQUID is proportional to the difference in the shielding currents induced in the pick-up loops in response to an external magnetic field gradient. The two pick-up loops are electrically in parallel, so one disadvantage of this topology is that even in a homogeneous field a large overall shielding current is induced in the outer perimeter of the pick-up loop structure with the potential to degrade noise performance through the associated production of large numbers of Abrikosov vortices in the superconducting film.

Another approach to the development of HTS transverse gradiometers employs a planar pick-up loop structure that is flip-chipped with a SQUID magnetometer to which it is inductively coupled. In the first-order designs(references) the flux transformer consists of a pair of pick-up loops, one of which is coupled to the SQUID magnetometer. By matching the mutual inductance between the SQUID and the loop, the total effective magnetic area of the SQUID/loop combination can be made exactly opposite to that of the other loop of the flux transformer. Under these conditions the sensitivity to a homogeneous magnetic field vanishes but remains non-zero with respect to a magnetic field gradient. A second-order transverse gradiometer has also been implemented using this approach(reference).

Any discussion of documents, acts, materials, devices, articles or the like which has been included in the present specification is solely for the purpose of providing a context for the present invention. It is not to be taken as an admission that any or all of these matters form part of the prior art base or were common general knowledge in the field relevant to the present invention as it existed before the priority date of each claim of this application.

Throughout this specification the word "comprise", or variations such as "comprises" or "comprising", will be understood to imply the inclusion of a stated element, integer or step, or group of elements, integers or steps, but not the exclusion of any other element, integer or step, or group of elements, integers or steps.

Throughout the following, the terms 'superconducting material', 'superconducting device' and the like are used to refer to a material or device which, in a certain state and at a certain temperature, is capable of exhibiting superconductivity. The use of such terms does not imply that the material or device exhibits superconductivity in all states or at all temperatures.

Summary of the Invention

According to a first aspect, the present invention provides a superconducting magnetic field detection element comprising at least one superconducting pick-up loop formed on a common flexible substrate, wherein the common flexible substrate is in a non-planar position, such that the at least one pick-up loop is operable to detect magnetic fields of differing orientation.

According to a second aspect, the present invention provides a method of forming an element of a superconducting device for detecting magnetic fields, the method comprising:

forming at least one pick-up loop on a common flexible substrate; and

positioning the common flexible substrate in a non-planar configuration such that the at least one pick-up loop is operable to detect magnetic fields of differing orientation.

By providing a device with two pick-up loops formed on the same substrate, the inherent characteristics of the two loops are likely to be significantly closer to each other than would be the case for the characteristics of pick-up loops or devices formed on separate substrates. Thus, the error margin of such devices can be expected to be significantly smaller, and indeed, magnetic fields of up to 10^6 lower than the earth's magnetic field may be detected by some embodiments of the present invention. Further, by using two pick-up loops, the present invention may enable magnetic field detection devices to be constructed which use only a single SQUID rather than requiring the extra complexity of providing a plurality of SQUIDs.

HTSC Axial Gradiometer Concept

The axial gradiometer of this invention shares some features of the second approach to the design of transverse gradiometers described above. This design is implemented through the use of a flux transformer pick-up loop structure patterned on flexible superconducting tape that is inductively coupled to a SQUID magnetometer.

Superconducting tape.

Superconducting tape has been developed primarily for power transmission applications. In early developments tape was formed using power in silver tube filled with one of the various ceramic HTS materials but more recently developments in tape technology has led to the ability to form YBCO films on both metal and insulating substrates with an intervening buffer layer.

The common flexible substrate may, for example, partially extend within a first plane and partially extend within a second plane substantially perpendicular to the first plane. When a magnetic dipole of random orientation is placed at a position where a normal to the first plane meets a normal to the second plane, such a configuration is advantageous, as the presence of the at least one pick-up loop in two perpendicular planes increases the likelihood that a magnetic field of the magnetic dipole will pass through at least some portion of the pick-up loop, and will thus induce a current in the pick-up loop, enabling detection of the magnetic dipole.

Alternatively, the common flexible substrate may be positioned such that the at least one pick-up loop describes an arc, for example an arc which subtends an angle of 90° about a nominal focus. In such embodiments, positioning a randomly oriented magnetic dipole at or near the nominal focus of the arc of the pick-up loop will provide a higher likelihood of detecting the magnetic dipole than would exist in cases where the pick up loop is positioned within a single plane.

The common flexible substrate may comprise of standard Hastelloy tape of 50 to 200 um thickness. Hastelloy tape is advantageous in that a pick-up loop of significantly larger area may be formed at significantly less cost, when compared to non-flexible crystalline substrates such as MgO, $SrTiO_3$, $LaAl_2O_3$ or the like. Alternatively, the common flexible substrate may comprise a partially or fully stabilised zirconia substrate, for example in very thin flexible sheet form, such as is provided under the name Ceraflex by MarkeTech International of 4750 Magnolia St, Port Townsend, WA, 98368, USA. Ceraflex has been found to possess improved noise properties over Hastelloy tape, enabling an SNR of a superconducting device formed over the substrate to be improved by perhaps 30%.

As such substrates are polycrystalline, a biaxially aligned buffer layer such as yttria-stabilised zirconia (YSZ) is preferably formed over the flexible substrate in order to improve biaxial alignment of a superconducting material

from which the at least one pick up loop is formed. The buffer layer may be deposited by ion beam assisted deposition (IBAD), or by double ion beam assisted deposition (DIBAD), as set out in the present applicant's pending International Patent Application No. PCT/AU02/00696, the contents of which are incorporated herein by reference.

These developments open the possibility of using these tapes as large area pick-up loops for magnetometers. In this design the applications of superconducting tape are extended to its use as a flexible superconducting medium for the fabrication of flexible superconducting circuits including gradiometer pick-up loops and flexible ground-planes for superconducting strip-lines. The concept should also be easily extended to form flexible superconducting wave-guides. In many of these applications even relatively short lengths of tape, of the order of a few hundred millimeters, would be sufficient.

<u>Axial Gradiometer Design</u>.

The gradiometer invention consists of a flux transformer that is formed by patterning an appropriate circuit using conventional resist techniques over the YBCO layer of the tape. The transformer/pick-up loop design pattern consists of a pair of outer primary loops which are connected in series with a centrally located secondary loop via a pair of flexible strip-line conductors. A SQUID magnetometer is then "flip-chipped" over the secondary loop of the transformer and separated from it by means of insulating spacers. A magnetic field which induces a current in the at least one pick up loop may be detected by use of a SQUID. The SQUID may be formed on the common flexible substrate, or alternatively may be magnetically coupled to the at least one pick up loop by way of a flux transformer formed on the common flexible substrate. Two additional lengths of tape are similarly used to cover the strip-line connectors with respect to which they form a ground-plane. These serve three purposes. Firstly to reduce any unwanted shielding currents which might otherwise be induced in the loop structure from the stripline, and secondly to reduce its inductance. The effect of the strip-line inductance on the performance of the gradiometer is considered in more detail below. Finally the ground-planes facilitate balancing of the equivalent areas of the primary pick-up loops by sliding the covering tapes to expose the appropriate area of strip-line to the external field.

In one embodiment of the invention, a plurality of pick up loops may be formed on the common flexible substrate, with the common flexible substrate arranged so as to position each of the plurality of pick up loops in a unique plane which is not parallel to or coplanar with any plane in which another pick up loop is positioned. For example, two pick up loops may be provided, and may be positioned in planes which are substantially perpendicular to each other.

A smallest radius of curvature of the common flexible substrate should be controlled. This is due to the possibility of an overly tight curvature of the device causing damage to the polycrystalline flexible substrate, the biaxially aligned buffer layer, the crystalline superconducting layer or any other layer such as an overlying silver passivating layer. Depending on the materials from which the common flexible substrate, the buffer layer, the superconducting pick up loops, and any other layers such as a passivation layer are formed, the minimum permissible radius of curvature of the device may vary.

The tape may also be twisted in order to provide circuit elements in a third plane, for example, to provide elements in three orthogonal planes. Once again, a minimum radius of curvature or twist is preferably controlled in order to avoid damage to the device.

According to a third aspect, the present invention provides a superconducting gradiometer comprising:

a first pick-up loop defining and substantially residing in a first nominal plane; and

a second pick-up loop defining and substantially residing in a second nominal plane;

wherein the first pick-up loop and the second pick-up loop are formed on a common substrate, wherein the first nominal plane and the second nominal plane are substantially parallel, and wherein the first nominal plane and the second nominal plane are sufficiently spaced apart to allow the first pick-up loop and the second pick-up loop to act to distinguish local magnetic fields from background magnetic fields.

By providing first and second pick-up loops which are formed on a common substrate, the third aspect of the present invention allows a gradiometer to be constructed without the need for separately formed connections between the first pick-up loop and the second pick-up loop.

The first pick-up loop and the second pick-up loop are preferably formed on a single flexible substrate which is positioned to provide the desired orientation of the first and second nominal planes.

The use of a flexible substrate allows formation of the superconducting gradiometer in a single plane, such as by planar deposition techniques. After the pick-up loops have been formed on the flexible substrate, deformation of the flexible substrate allows the first and second pick-up loops to be respectively positioned in the first and second nominal planes.

When used, the flexible substrate preferably comprises a flexible tape made of a rolled metal alloys such as Hastelloy. Advantageously, a Ceraflex tape may be used. In the past, Ceraflex tapes have not been used for HTS applications, however it has been realised that Ceraflex tape provides improved noise performance over traditional tapes such as Hastelloy tape, improving the SNR of a device formed on the tape by perhaps 30%.

A buffer layer may be positioned between the substrate and the pick-up loops, for example to promote biaxial crystal alignment in superconducting material from which the pick-up loops are formed, and/or to isolate the superconducting material from the substrate. The buffer layer may comprise a biaxially aligned yttria-stabilised zirconia (YSZ) layer. The superconducting material may be $YBa_2Cu_3O_7$ (abbreviated as YBCO) or $Bi_{1.6}Pb_{0.4}Sr_2Ca_2Cu_3O_{10}$ (abbreviated as BSCCO). A protective layer such as an Ag layer can be provided over the superconducting material from which the pick-up loops are formed.

In preferred embodiments of the third aspect of the invention, a flux transformer is provided between the first and second pick-up loops in order to couple detected flux into a SQUID proximal to the flux transformer. For example, a SQUID may be formed by conventional means on a separate substrate and "sandwich-mounted" against the flux transformer, in a “flip-chip” arrangement as described previously.

Alternatively, a SQUID may be formed on the flexible substrate itself, by formation of a Josephson Junction over a step edge etched into the substrate.

According to a fourth aspect, the present invention resides in a method of fabrication of a superconducting gradiometer comprising the steps of:

forming a first pick-up loop and a second pick-up loop on a flexible substrate positioned substantially in a single nominal plane; and

subsequently deforming the flexible substrate to position the first pick up loop substantially in a first nominal plane and to position the second pick-up loop substantially in a second nominal plane, wherein the first nominal plane and the second nominal plane are substantially parallel and are spaced sufficiently apart to allow the first pick-up loop and the second pick-up loop to act to distinguish local magnetic fields from background magnetic fields.

The method of the fourth aspect of the invention may comprise the additional steps of:

forming a flux transformer on said flexible substrate; and

sandwich mounting a SQUID against the flux transformer.

It will be appreciated that the step of forming a flux transformer may be most conveniently carried out simultaneously with the step of forming said first and second pick-up loops.

Alternatively, the method of the fourth aspect of the invention may comprise the additional steps of:

forming a step edge on the flexible substrate; and

forming a SQUID on the flexible substrate, having a Josephson Junction formed over said step edge.

The method of the fourth aspect of the invention may comprise the additional steps of:

forming a buffer layer over the flexible substrate prior to formation of said pick-up loops; and/or

forming a protective coating over the first and second pick-up loops.

The buffer layer may be biaxially aligned YSZ, and may serve to promote biaxial growth of superconducting material from which the pick-up loops are formed, and may serve to isolate the pick-loops from the substrate. The protective coating may be a silver coating.

To date, HTS flexible tapes have mainly been considered for power transmission purposes. Thus, it is envisaged that a relatively thin superconducting layer of perhaps 50-500 nm may be used in the present invention, as opposed to thicker power-carrying superconducting layers.

Brief Description of the Drawings

By way of example only, preferred embodiments of the invention will be described with reference to the accompanying drawings, in which:

Figure 1 illustrates a HTS gradiometer in accordance with a first embodiment of the present invention;

Figure 2 illustrates a magnetic field detection element in accordance with a second embodiment of the present invention;

Figure 3 illustrates a magnetic field detection element in accordance with a third embodiment of the present invention;

Figure 4 illustrates a HTS gradiometer in accordance with a fourth embodiment of the present invention;

Figure 5 illustrates the variation of the magnetometer current and gradient sensitivity with the stripline inductance of 20 nH;

Figure 6 illustrates the variation of the magnetometer current and gradient sensitivity with the stripline inductance of 5 nH and

Figure 7 illustrates the variation of the magnetometer current and gradient sensitivity with the stripline inductance of 0.5 nH.

Description of the Invention

Figure 1 illustrates a .high temperature superconducting (HTS) gradiometer 10 in accordance with an embodiment of the first aspect of the present invention. The gradiometer comprises a flexible Hastelloy tape 11, providing a substrate for superconducting elements of the gradiometer. A buffer layer of YSZ has been grown over a surface of the Hastelloy tape to enhance biaxial alignment of YBCO formed over the YSZ. A first pick-up loop 12 formed of YBCO is provided proximal to one end of the tape 11, and a second pick-up loop 13 also formed of YBCO is provided proximal to an opposite end of the tape 11. The pick-up loops are connected to each other via tracks 14 and flux transformer 15 in a manner which cancels out common-mode magnetic fields such as the earth's magnetic field, such that only a magnetic field which has a gradient between the first and second pick-up loops will cause current to flow in the superconducting YBCO elements 11, 12, 13, 14, 15.

As can be seen, all superconducting elements of the gradiometer 10 can be fabricated on a single surface of the tape 11, and can be formed while positioned in a single plane using planar deposition technologies, see Fig 1b. Further, due to the flexibility of the Hastelloy tape, once fabricated the first and second pick-up loops 12, 13 can be axially aligned and positioned a distance *d* apart.

A SQUID, not shown, may then be "sandwich mounted" to the Hastelloy tape 11 so as to be in close proximity to the flux transformer 15 and to maximise magnetic coupling between the SQUID and the flux transformer 15. Thus, when current is induced in the flux transformer 15 by a magnetic field having a gradient between the first and second pick up loops 12, 13, the current circulating in the flux transformer 15 will induce another magnetic field, which will be coupled to the SQUID for detection.

By using only a single SQUID, the present invention enables a HTS gradiometer to be constructed which does not suffer from the deficiencies associated with measurements relying on the measurements obtained by two different SQUIDs having differing inherent characteristics. Further, by using a flexible Hastelloy tape or the like, the present invention enables a single SQUID HTS gradiometer to be constructed, as flexible HTS circuits may be formed on such a substrate.

Figure 2 illustrates a magnetic field detection element 20, in accordance with an embodiment of the first aspect of the present invention. The magnetic field detection element 20 comprises a first pick up loop 21, a flux transformer 22, and a second pick up loop 23 not visible but of equal dimensions as pick up loop 21. The pick-up loops 21 and 23 and the flux transformer 22 are formed on a flexible substrate comprising a Ceraflex tape 25. A buffer layer of YSZ (not shown) is formed over the tape 25, and the pick-up loops 21, 23 and the flux transformer 22 are formed of YBCO deposited over the buffer layer. Tracks 24 connect pick-up loops 21, 23 with flux transformer 22.

In accordance with the present invention, the flexible substrate 25 is arranged such that the pick-up loop 21 is positioned in a first plane which is substantially perpendicular to a second plane in which the second pick-up loop 23 is positioned. As indicated at 26, 27, the normals to the planes in which the pick-up loops 21, 23 are positioned meet at substantially 90 degrees.

Accordingly, when a magnetic dipole is positioned with random orientation where the normals 26, 27 meet, the magnetic detection element 20 is more likely to detect the magnetic dipole than prior art arrangements in which a pick-up loop is provided in one plane only. For example, if the magnetic dipole is aligned along axis 27, the field of the dipole will couple strongly through pick-up loop 23, but will not couple strongly into pick-up loop 21. If the magnetic dipole is aligned along axis 26, the field of the dipole will couple strongly into pick-up loop 21, but will not couple strongly into pick-up loop 23. If

the dipole is aligned at 45 degrees to each axis 26, 27, the field of the dipole will couple with equal strength into each pick-up loop.

When a field couples into one or both of pick-up loops 21, 23, current will be induced. This current will be passed to flux transformer 22, which is preferably designed so as to maximise magnetic coupling to a SQUID (not shown) which is to be sandwich mounted onto the tape 25. Detection of the magnetic field of the dipole can then be carried out with high sensitivity by the SQUID.

Figure 3 illustrates a magnetic field detection element 30 in accordance with another embodiment of the first aspect of the present invention. The element 30 comprises a first pick-up loop 31, a flux transformer 32 and a second pick-up loop 33. Pick-up loop 31 subtends an angle θ of greater than 90 degrees. Consequently, a magnetic dipole aligned along an axis anywhere within angle θ, will couple relatively strongly through pick-up loop 31. Similarly, a magnetic dipole with an axis which is aligned anywhere within the angle subtended by pick-up loop 33 will couple relatively strongly through pick-up loop 33. A stronger coupling will induce greater current in the pick-up loops 31, 33, and thus provide a stronger signal for detection by a SQUID sandwich mounted over flux transformer 32.

According to a further embodiment there is shown in Figure 4 an HTS gradiometer 40 having a first pick-up loop 42, a second pick-up loop 44 and a flux transformer 46. Each of the pick-up loops 42, 44 are directly linked to a secondary loop of the flux transformer 46 via respective strips 48 and 50. Each of the pick-up loops 42, 44 and the secondary loop of the flux transformer 46 may each be formed of YBCo material. They are each fabricated on a flexible Hastelloy tape 52, shown in Figures 4(b) and 4(c) as shading. These two figures 4(b) and 4(c) also show the gradiometer 40 assembled prior to bending the stripline connector sections 48 and 50.

The first pick-up loop 42 has internal dimensions d_{p1}, d_{p2} and external dimensions D_{p1}, D_{p2}. The second pick-up loop 44 has similar dimensions to that of the first pick-up loop 42 and the secondary loop of the flux transformer 46 has an internal length d_S and external length D_S. A SQUID may be sandwich mounted to the Hastelloy tape 52 of which a pick-up loop 54 is shown which is in close proximity to the secondary loop of the flux transformer 46 to establish a magnetic coupling therebetween. The magnetometer pick-up loop 54 has inductance L_M and area A_M, the secondary loop of the flux transformer

has inductance L_S and effective area A_S. Each of the pick-up loops 42 and 44 respectively have inductance L_1, L_2 and equivalent areas A_1 and A_2 respectively.

Shown in Figure 4 (c) is the gradiometer having each of the pick-up loops 42 and 44 in parallel planes separated by distance d with the stripline connectors 48, 50 bent with a radial curvature r. Magnetic field B_Z is shown normal to the SQUID and flux transformer 46 whilst the magnetic field impinging on the primary loop 42 is B_{X1}-B_X+(d/2)g_{XX} and the field impinging on the second pick-up loop 44 is B_{X2}-B_X-(d/2)g_{XX}. Thus when current is induced in the secondary loop 46 of the flux transformer by magnetic field having a gradient between the first and second pick-up loops 42, 44, the current circulating in the secondary loop 46 induces a further magnetic field which couples with the pick-up loop 54 of the SQUID thereby inducing a further current which is detected by the SQUID.

With regard to the design of the axial gradiometer, the strip-line sections are folded to form a "U" shape with the primary pick-up loops aligned on a common axis that is then perpendicular to the axis of the SQUID. Since the SQUID is oriented perpendicularly to the gradient pick-up loops, and assuming the orientation, this device is sensitive to both the first-order axial gradient, $\partial B_x/\partial x$, and to the transverse component of the magnetic field B_z. For applications in which the sensitivity to B_z must be reduced, this can be achieved by appropriate design of the secondary loop and SQUID to ensure shielding of the magnetometer by currents induced in the secondary pick-up loop. The pick-up loop structure so formed is a series type. This decreases the magnitude of the shielding current which results from the components of any external homogeneous magnetic fields in the plane normal to the SQUID axis.

Currents in the pick-up loops are induced only by a field gradient in the x − direction, mismatches between the magnetic equivalent areas of the primary loops, direct exposure of the strip-lines to the external field or by incorrect mutual inductance between the secondary loop and the SQUID.

The axial gradiometer may also be mounted such that it is possible to rotate the gradiometer device either the SQUID and pick up loop together or the pick up loop with the SQUID stationary to achieve further improvements to the device usefulness. These improvements are:

- true value of the gradient field and magnetic field,
- greatly enhanced common mode rejection of homogeneous fields
- real time information of the condition of the SQUID operation
- if three axial gradiometers are mounted near orthogonally or orthogonally, jointly they provide all five unique components of the first order gradient tensor and the three components of the total field
- these improvements can be achieved without the need to attain perfect balance usually achieved by the physical alignment of the pick up loops of the flexible tape.

Rotation of axial gradiometers of both HTS axial gradiometers described here and LTS axial gradiometers provides the above enhancements.

Theory of Operation.

Assume a lumped inductance model with all mutual inductances regarded as negligible other than the mutual inductance, M, between the secondary loop of the flux transformer and the magnetometer. In what follows it is assumed that the magnetometer employed is a SQUID based directly-coupled magnetometer. In this type of magnetometer a superconducting pick-up loop is used to sense the external magnetic field. The inductance and equivalent area of the magnetometer pick-up loop will be denoted L_m and A_m respectively. Currents induced in this loop are injected into a SQUID amplifier that has a geometry optimized for minimum flux noise. A magnetometer of this type is assumed for two reasons. Firstly these devices currently provide the best sensitivity possible from HTSC SQUID based magnetometers, and are therefore likely candidates for a practical device. Secondarily, as will be seen below, the alternative choice of a DC or RF SQUID with a flux-focussing washer, can be regarded as a special case of the present theory.

Since the magnetometer is coupled to the transformer secondary by a short-circuit superconducting loop, the flux in this loop is conserved with respect to changes in the external field. The total flux in the magnetometer pick-up loop is the sum of the fluxes due to the external field, its own shielding current and the flux coupled via the mutual inductance M from the current I, in the secondary loop of the transformer. Assuming, without loss of generality, that the device is zero field cooled (Z.F.C), this sum vanishes, i.e.

$$B_z A_m - I_m L_m - MI = 0$$

The flux transformer is also a shorted superconducting loop, so once again assuming it is Z.F.C

$$B_{x2} A_2 - B_{x1} A_1 - IL + B_z A_s - I_m M = 0$$

where L is the total inductance of the transformer, i.e.: $L = L_1 + L_2 + 2L_c + L_s$.

L_k, A_k denote the inductance and equivalent area of the primary loop k, $(k = 1,2)$, L_c in the inductance of each of the strip-lines and L_s is the inductance of the secondary loop.

Solving equations and simultaneously gives for the magnetometer current

$$I_m = \frac{dMA g_{xx} - B_z[A_m L - MA_s]}{M^2 - L_m L}$$

where $A_1 = A_2 \triangleq A$, and

$$B_{x2} - B_{x1} = \left(B_x + \frac{d}{2} g_{xx}\right) - \left(B_x - \frac{d}{2} g_{xx}\right)$$
$$= d g_{xx}$$

This can be re-written in terms of the coupling constant α by use of the standard relation

$$M = \alpha \sqrt{L_m L_s}$$

to yield

$$I_m = \frac{B_z\left(A_m \frac{L}{L_m} - \alpha A_s \sqrt{\frac{L_s}{L_m}}\right) - \alpha d A g_{xx} \sqrt{\frac{L_s}{L_m}}}{2(L_p + L_c) + L_s(1 - \alpha^2)}$$

where $L_1 = L_2 \triangleq L_p$.

<u>Condition for shielding to suppress sensitivity to B_z.</u>:

If the external field is homogeneous $g_{xx} = 0$ and equation becomes

$$I_m = B_z \frac{A_m \frac{L}{L_m} - \alpha A_s \sqrt{\frac{L_s}{L_m}}}{2(L_p + L_c) + L_s(1 - \alpha^2)}$$

which vanishes if

$$\frac{A_m}{A_s} = \frac{\alpha\sqrt{L_m L_s}}{2L_p + 2L_c + L_s} = \frac{M}{L}$$

Optimization and gradient sensitivity.

If is fulfilled, . equations and for the magnetometer current, become simply

$$I_m = -dA g_{xx} \frac{M}{L_m L - M^2}$$

$$= -dA\, g_{xx} \frac{\alpha\sqrt{\frac{L_s}{L_m}}}{2(L_p + L_c) + L_s(1 - \alpha^2)}$$ *

To study the behaviour of eqn. note that in general both A, the equivalent area of the primary loops of the transformer, and L_P depend upon the dimensions of the primary loop . As far as the applicant is aware exact forms for these relations do not exist for either square or rectangular superconducting structures and it is usual to resort to empirical formulae. which are motivated either by experiment or numerical simulation. The following empirical relations will be used in which $d_p \triangleq (d_1 + d_2)/2$ and

$$D_p \triangleq (D_1 + D_2)/2$$

$$A = \gamma_p d_p D_p$$

where $0.8 \lesssim \gamma_p \lesssim 1$ is approximately constant,

$$L_p = \mu_0 d_p \left(e^{-\pi(D_p - d_p)/2d_p} + 1.2\right)$$

provided that $(D_p - d_p)/2d_p \gtrsim 0.1 \Rightarrow D_p > 1.2 d_p$.

Equation is the widely accepted form for the equivalent area of a square washer[Ketchen1] in which the average values of the inner and outer dimensions of the rectangular loop are used.

Use of these relations in equation * above gives

$$\frac{I_m}{dg_{xx}} = \gamma_p \alpha d_p D_p \frac{\sqrt{L_s}}{\sqrt{L_m}} \times \left[2L_c + L_s(1-\alpha^2) + 2\mu_0 d_p \left(e^{-\pi(D_p-d_p)/2d_p} + 1.2\right) \right]^{-1}$$

Shown in Figures 5, 6, 7 are plots plotted as a function of d_p and α for three different values of L_c, namely 20_{nH}, 5_{nH} and 0.5_{nH} respectively. Other parameters are set as follows: $D_p = 0.01, \gamma_p = 0.9, L_m = 5_{\mathrm{nH}}$, $L_s = 10_{\mathrm{nH}}$.

It will be appreciated by persons skilled in the art that numerous variations and/or modifications may be made to the invention as shown in the specific embodiments without departing from the spirit or scope of the invention as broadly described. For example, a device similar to that shown in Figure 3 may comprise a single pick-up loop only, subtending an arc in order to increase a range of magnetic dipole orientations which can be detected by the pick-up loop. Further, such devices may comprise a SQUID fabricated on the tape itself in place of the flux transformer, such that the current of the pick-up loops flows directly into the SQUID for detection.

The present embodiments are, therefore, to be considered in all respects as illustrative and not restrictive.

Dated this 7th day of August 2002

Commonwealth Scientific and Industrial Research Organisation
Patent Attorneys for the Applicant:

F B RICE & CO

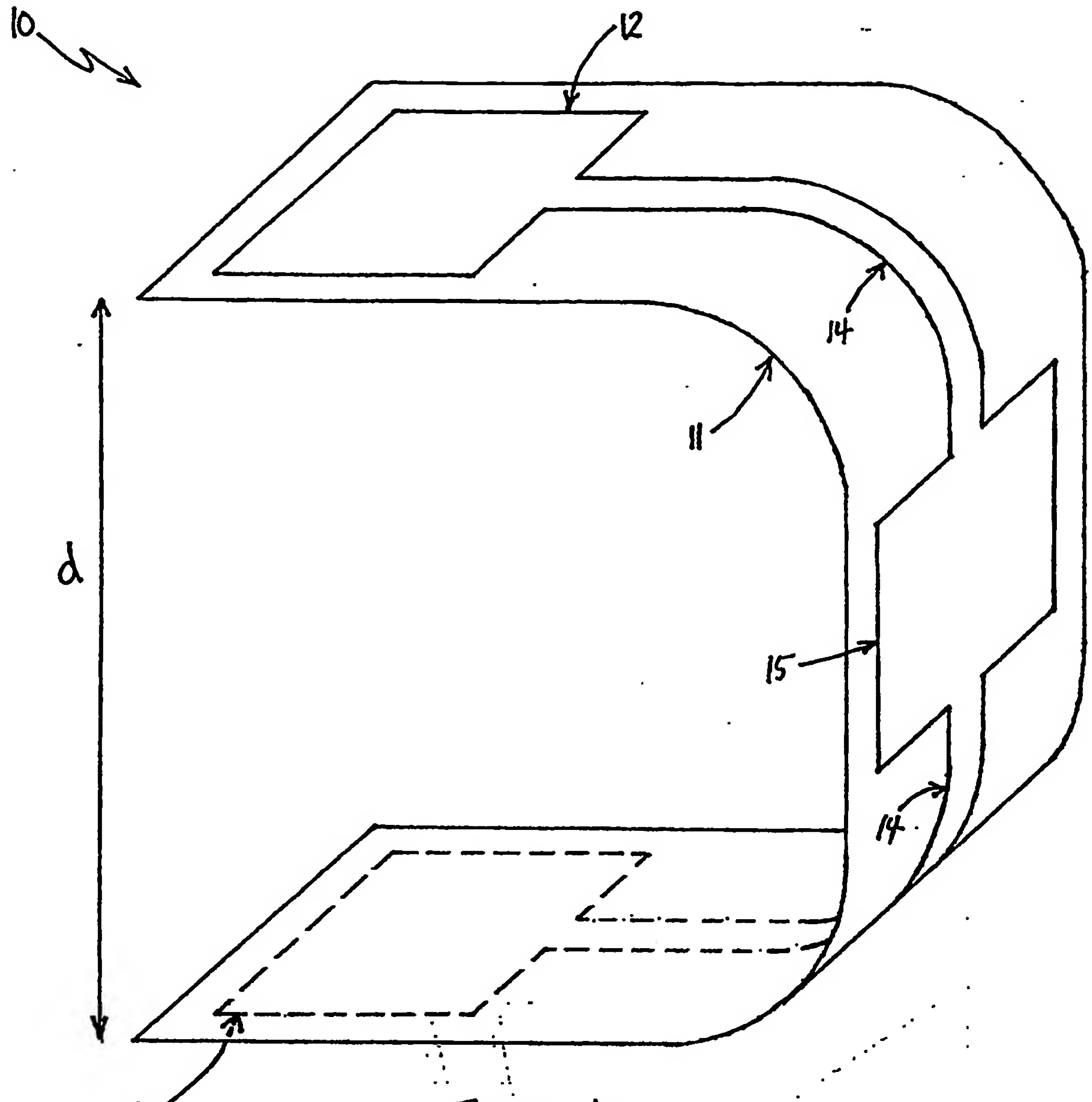

FIGURE 1A

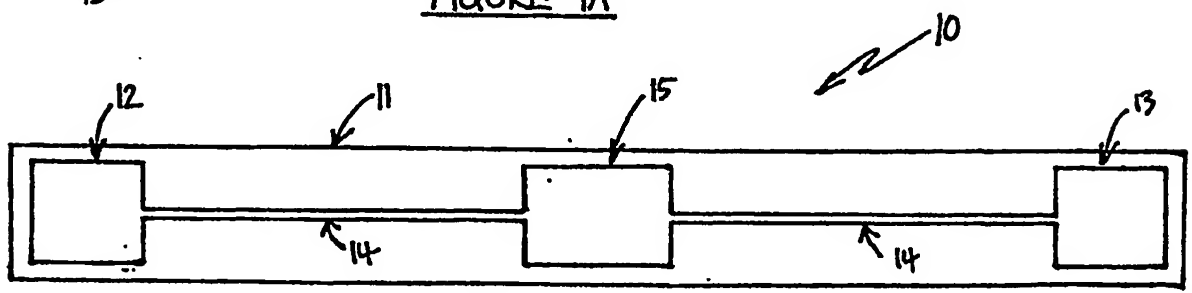

FIGURE 1B.

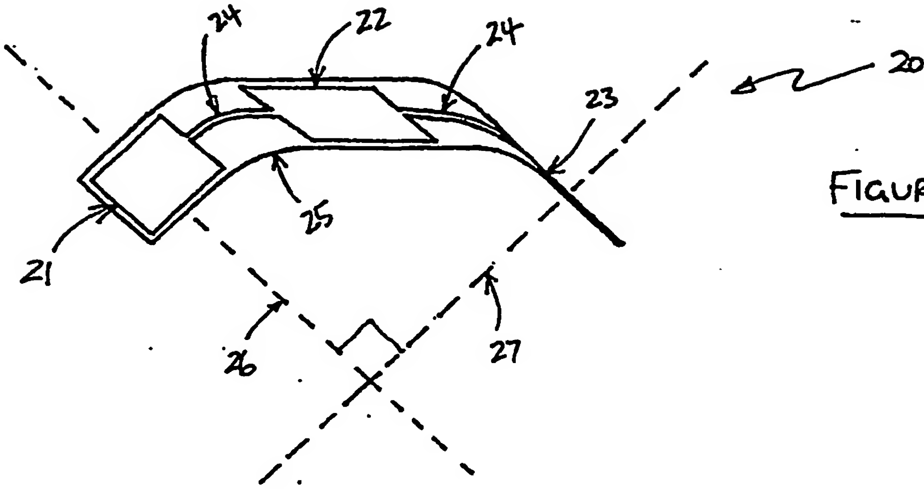

FIGURE 2

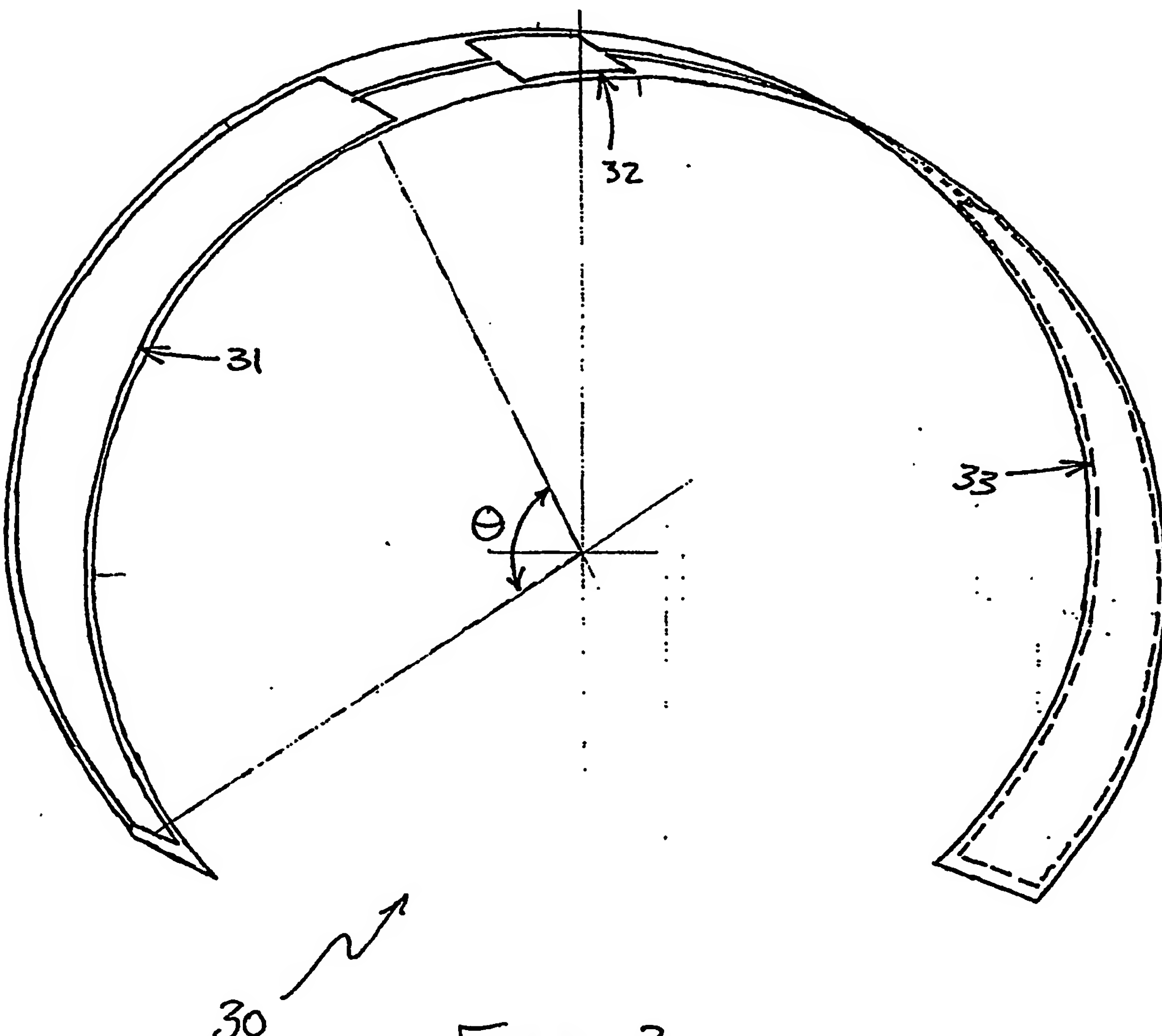

FIGURE 3

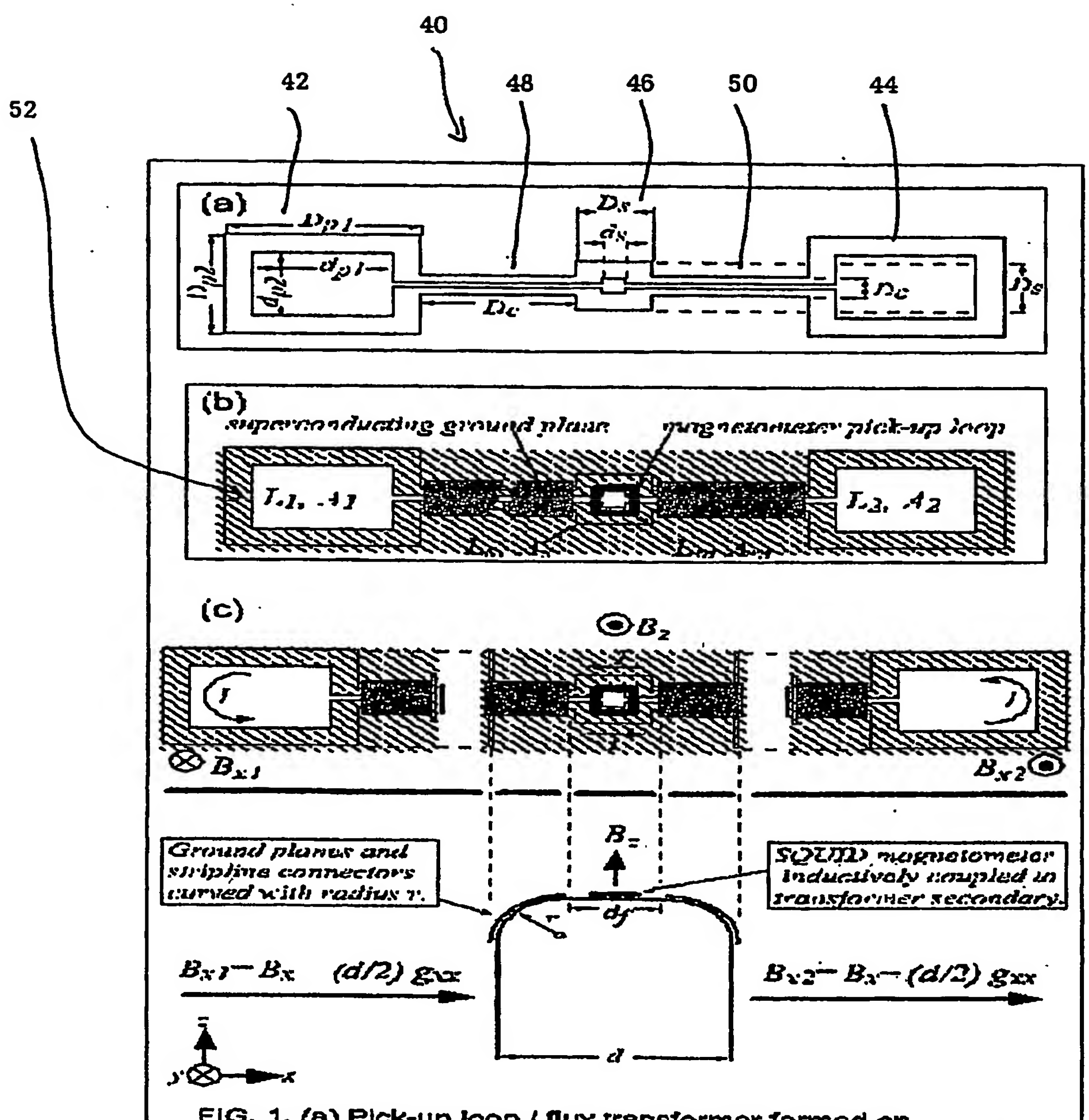

FIG. 1. (a) Pick-up loop / flux transformer formed on superconducting tape. (b) Complete gradiometer assembled prior to bending the strip-line connector sections. (c) Four - perspective view of the complete axial gradiometer.

FIGURE 4

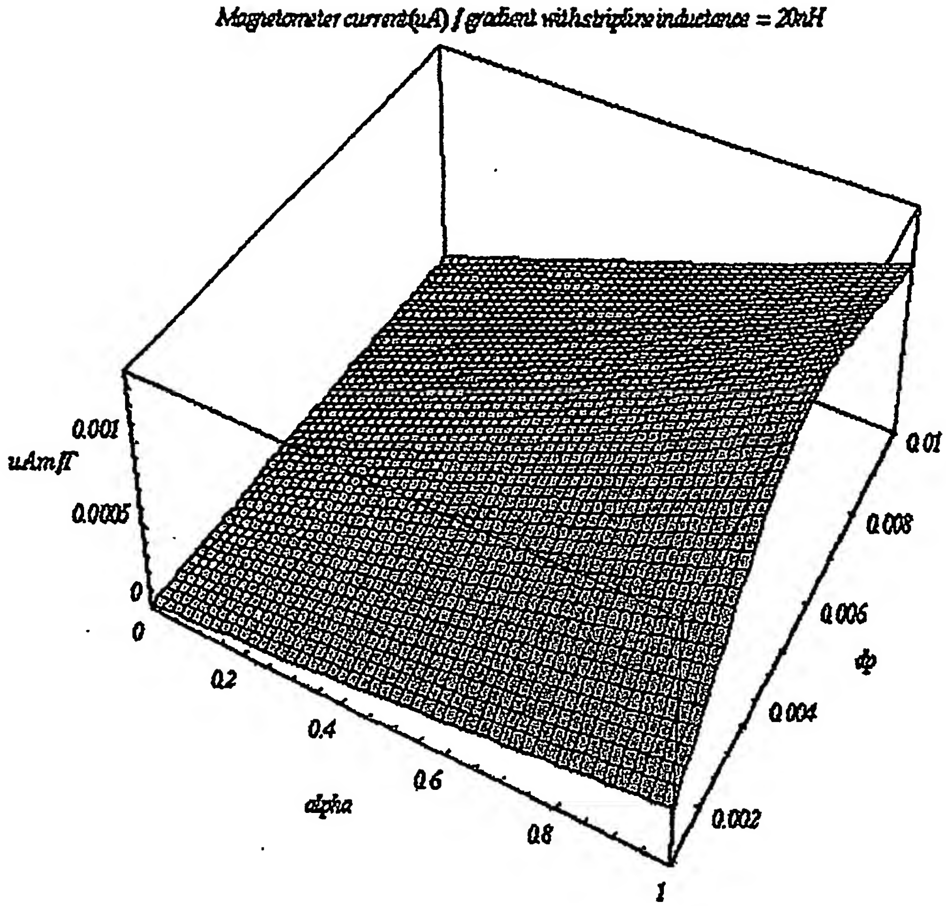
Magnetometer current(uA) / gradient with stripline inductance = 20nH
0.001
uAm/T
0.0005
0
0
0.2
0.4
0.6
alpha
0.8
1
0.002
0.004
0.006
dp
0.008
0.01

FIGURE 5

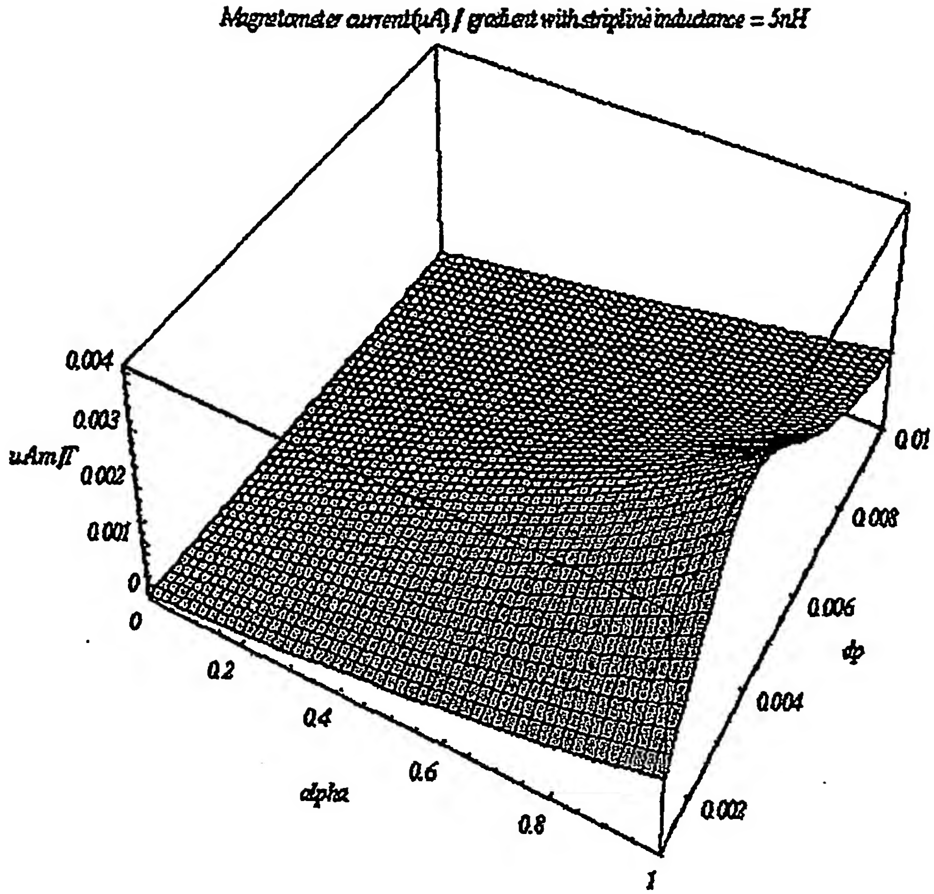
Magnetometer current(uA) / gradient with stripline inductance = 5nH
0.004
0.003
uAm/T
0.002
0.001
0
0
0.2
0.4
0.6
alpha
0.8
1
0.002
0.004
0.006
dp
0.008
0.01

FIGURE 6

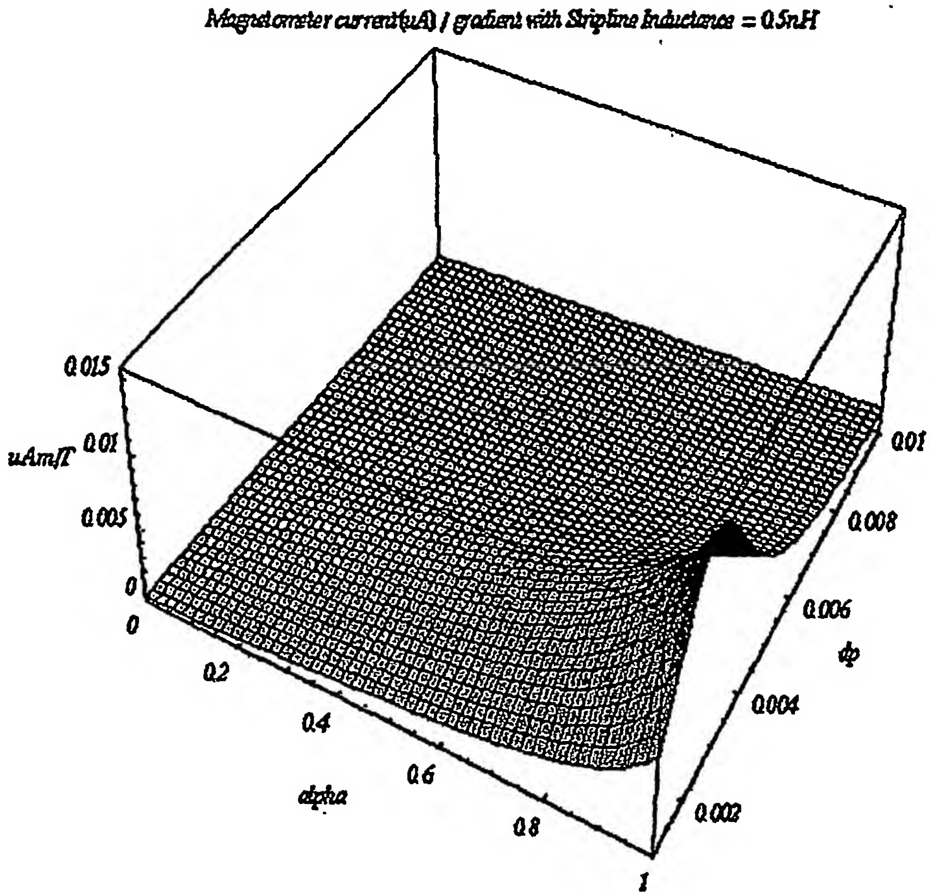
Magnetometer current(uA) / gradient with Stripline Inductance = 0.5nH
0.015
0.01
uAm/T
0.005
0
0
0.2
0.4
0.6
alpha
0.8
1
0.002
0.004
0.006
dp
0.008
0.01

FIGURE 7